Gunn Diodes represent an example of negative differential resistance (NDR) devices.

Why achieving the NDR is so attractive?

Power dissipated in the diode = $I^2 \times R_d < 0$

The NDR diode can serve as an amplifier or oscillator without any external circuits providing a feedback.
The NDR can be easily achieved in ANY semiconductor diode

\[ n = \sqrt{N_v N_c} \ e^{\frac{-E_G}{2kT}} \]

\[ R = \frac{1}{q n \mu S} \ L = \frac{1}{q(\sqrt{N_v N_c}) \mu S} \ \frac{E_G}{e^{2kT}} = B e^{2kT}; \text{where } B = \frac{1}{q(\sqrt{N_v N_c}) \mu S} \ L \]

When the current flows through the sample, the sample temperature increases due to Joule heating

\[ \Delta T = R_T P = R_T I.V; \]

\[ T = T_0 + \Delta T = T_0 + R_T I.V; \]

Therefore,

\[ R = B e^{2kT} = B e^{2k(T_0 + \Delta T)} = B e^{2k(T_0 + R_T I.V)} \]

\[ V = IR = I B e^{2k(T_0 + R_T I.V)} = IB e^{(T_0 + R_T I.V)} \]
The NDR due to a self-heating:

\[ R = B e^{\frac{E_G}{2kT}} = B e^{\frac{E_G}{2k(T_0 + \Delta T)}} = B e^{\frac{E_G}{2k(T_0 + R_T IV)}} \]

At low powers the resistance does not depend on the power.
The NDR due to a self-heating

\[ V = IR = IB e^{2k(T_0 + R_T IV)} = \alpha e^{(T_0 + R_T IV)} \]

At high powers the temperature rise increases the concentration and the resistance decreases
Load-line method for electric circuit with NDR

Solution: the lowest current after turn on
Thermistor with NDR as a temperature sensitive switch (Fire Alarm)

Solution at 77 C VERY HIGH CURRENT – FIRE ALARM!

Solution at 27 C – very low current (<1 mA)
Gunn Effect (Transferred Electron) NDR devices

First Observation

![Diagram of n-GaAs device with current and voltage axes showing "Noisy" current]

n-GaAs

J. B. Gunn, 1963

I

V

"Noisy" current

J. B. Gunn, 1963
11 Gunn Effect (Transferred Electron) devices

First Observation

J. B. Gunn, 1963

\[ v = 0.2 \text{ cm/20 ns} = 10^7 \text{ cm/s} \]

J. B. Gunn, 1963
Ridley-Watkins-Hilsum-Gunn Effect

B.K. Ridley, 1963:
"Domain instability should occur in a semiconductor sample with a negative differential resistance"

In GaAs, InP and other III-V compounds, the differential mobility may become negative at high electric fields

\[ \mu_d = \frac{\partial \nu}{\partial F} < 0 \]

So does the differential conductivity:

\[ \sigma_d = q\eta\mu_d < 0 \]
The negative slope of the $v$ vs. $F$ characteristic develops as a consequence of the \textit{intervalley} transition of electrons from the central $\Gamma$ valley of the conduction band into the satellite valleys.

When the electric field is low, electrons are primarily located in the central valley of the conduction band. As the electric field increases, many electrons gain enough energy from the electric field for the intervalley transition into the satellite valleys.
The electron effective mass in the L and X valleys of the conduction band is much greater than in the Γ valley. Also, the intervalley transition is accompanied by an increased intervalley scattering.

These factors result in *the decrease of the electron velocity in high electric fields*.
The mechanism of negative differential mobility in GaAs and other III-Vs

When the electric field is low, practically all electrons are in the lowest minimum of the conduction band and the electron drift velocity $v$ is given by

$$v_1 = \mu F$$

where $\mu$ is the low-field mobility and $F$ is the electric field.

In a higher electric field electrons are "heated" by the field and some carriers may have enough energy to transfer into upper valleys where the electron velocity is

$$v_2 \approx v_s$$

Here $v_s$ is the saturation velocity.

The current density is given by

$$j = qv_1(F)n_1 + qv_2(F)n_2$$

where $n_1$ is the electron concentration in the lowest valley and $n_2$ is the electron concentration in the upper valley:

$$n_1 + n_2 = n_o, \text{ where } n_o \approx N_D.$$
The mechanism of negative differential mobility in GaAs and other III-Vs

We can define an average drift velocity of all the electrons, \( v_s \) as

\[
v = \frac{v_1 n_1 + v_2 n_2}{n_0}
\]

or

\[
v \approx \mu F n_1(F) + v_s n_2(F)
\]

In order to find the electric field dependence of \( v \), we need to know the \( n_2(F) \) dependence
The fraction of electrons in the upper valleys $p = n_2/n_0$ can be approximate as

$$p = \frac{A(F/F_S)^t}{1+(F/F_S)^t}$$

where $F_S = v_s/\mu$, $A \sim 0.6$ and $t \sim 4$ for GaAs.

The exact expressions for GaAs are:

$$A = 0.6[e^{10(\mu - 0.2)} + e^{-35(\mu - 0.2)}]^{-1} + 0.01$$
$$t = 4[1 + 320/\sin h(40\mu)]$$
$$v_s = 0.6 + 0.6\mu - 0.2\mu^2(10^5 \text{ m/s})$$
An important results that follows from $v(F)$ dependence:

$$v = \frac{\mu F n_1(F) + v_s n_2(F)}{n_0}$$

is that the differential mobility,

$$\frac{dv}{dF} = \mu(1-p) + (v_s - \mu F) \frac{dp}{dF}$$

becomes NEGATIVE if:

$$\frac{dp}{dF} > \frac{1-p}{F - F_s}$$

This occurs if the electric field exceeds the critical value $F_p \sim F_s$.

For GaAs, $F_p \sim 3.5 \text{ kV/cm}$
This approximation gives a good agreement with Monte Carlo simulations and experimental data.

\[ v \approx \frac{\mu F n_1(F) + v_s n_2(F)}{n_0} \]
Instabilities in the samples with bulk NDR

The negative differential resistance may lead to a growth of small fluctuations in the space charge in a sample.

A simplified equivalent circuit may be presented as a parallel combination of the differential resistance

\[ R_d = \frac{L}{q\eta \mu_d S} \]

and the differential capacitance:

\[ C_d = \frac{\varepsilon S}{L} \]

Remember, \( \varepsilon \equiv \varepsilon \varepsilon_0 \) here!

The RC time constant:

\[ \tau_d = R_d C_d = \frac{\varepsilon}{qN_d \mu_d} \]

This time constant is called the Maxwell differential dielectric relaxation time.
Instabilities in the samples with bulk NDR

\[ \tau_d = R_d C_d = \frac{\varepsilon}{qN_d \mu_d} \]

In a material with a positive differential conductivity, a space charge fluctuation, \( \Delta Q \), decays exponentially with time:

\[ \Delta Q = \Delta Q(0).\exp(-t/\tau_d) \]

where \( \Delta Q(0) \) is the magnitude of the fluctuation at \( t = 0 \).

When the differential conductivity is negative the space charge fluctuation may actually grow with time

\[ \Delta Q = \Delta Q(0)\exp(t/\tau_d) \]
Let the average field in the sample be greater than $F_p$:

1. The sample has a fluctuation of electron concentration;
2. This fluctuation leads to an electric field fluctuation: \[ \frac{\partial F}{\partial x} = q(n - n_0) \]
3. In the higher-field region the electrons “slow down”
4. These slow electrons INCREASE the original concentration fluctuation.

Remember, $\varepsilon = \varepsilon \varepsilon_0$ here!
The fluctuation develops in such a way that the accumulation layer remains “behind” and the “front edge” is depleted with electrons.
At the same time the entire fluctuation drifts towards the positive contact (the anode) with the velocity of the “slow” electrons, i.e. $v_s$.

If the sample is long enough, the fluctuation develops into a “high-field domain”
What time is needed to develop a high-field domain?

The characteristic time of the space charge growing is \( \sim 3\tau_d \):

\[
\tau_d = R_d C_d = \frac{\varepsilon}{qN_d \mu_d}
\]

During the time of \( 3\tau_d \) the domain travels the distance:

\[
L_{tr} \sim v_s \cdot 3\tau_d
\]

Therefore the instability occurs if

\[
L > 3v_s \cdot \tau_d
\]

This leads to the so-called Kroemer criterion for the Gunn instabilities:

\[
n_0L > (n_0L)_1 = \frac{3\varepsilon v_s}{q|\mu_d|}
\]

Remember, \( \varepsilon = \varepsilon \varepsilon_0 \) here!

For GaAs \( \mu_d \sim 0.07 \text{ m}^2 /\text{V-s} \)

Derive the Kroemer criterion
When the sample parameters meet the Kroemer criterion, a high-field domain periodically develops at the cathode side, drifts towards the anode and dissolves there.

- There is always ONE and ONLY ONE domain propagating in the sample if the applied voltage is above the threshold and constant.
- The current decreases with the domain formation and increases when the domain dissipates.
- The oscillation frequency (the “transit time” frequency), $f_T \sim \frac{v_s}{L}$
The NDR and domain formation mechanisms explain Gunn’s observations.

Find the diode length and the required doping level for GaAs sample to have Gunn instability with the domain transit time of 100 ps

\[ n_0 L > (n_0 L)_1 = \frac{3e v_s}{q|\mu_d|} \]

For GaAs \( \mu_d \sim 0.07 \text{ m}^2/\text{V-s} \)
and \( v_s \sim 10^5 \text{ m/s} \)